An Improved Adaptive Control System for a Two Wheel Inverted Pendulum-Mobile Robot using Eagle Strategy with a Particle Swarm Optimization

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Abstract: In this paper, natures stimulating algorithm Eagle strategy with Particle Swarm Optimization (ESPSO) technique is proposed to a Two Wheel Inverted Pendulum-Mobile Robot (TWIP-MR) stability analysis. The uniqueness of the inverted pendulum system has drawn interest from many researches due to the unstable nature of the system. The idea of a mobile inverted pendulum robot has surfaced in recent years and has attracted interest from control system researchers worldwide. The TWIP-MR is a multi-input and multi output system. This system is an open loop Unstabilized system with non-linear behavior according to stability concern. The main task of this design is to keep the balance of the robot while it is moving towards the desired position. While designing TWIP-MR two loops are presented one is for balancing the linear displacement and other loop is to keep the desired angular movement. In this paper concentrated on Simulink Blocks and their graphs are analyzed with the help of mathematical approach.

Index Terms **- Two-wheeled Inverted Pendulum Mobile Robot, ESPSO, stability, Optimization.**

I. Introduction

As the Robot is mechanically unstable, it becomes necessary to explore the possibilities of implementing a control system to keep the system in equilibrium. As the Robot is moving on a surface, a conventional PID controller is implemented to control the trajectory of the robot.

The instability of inverted pendulum system has always been an excellent test bed for control theory experimentation. Therefore it is also the aim of this paper to investigate the suitability and examine the performance linear control systems conventional techniques like the linear quadratic regulator (LQR), pole-placement technique and Model Reference Adaptive System (MRAS) in stabilizing the system where control designs involve compromises between conflicting goals.

In general, for the PID control design, a compromise has to be made between performance and robust stability. In LQR design main issue is to trade-off attenuation of the process disturbances and the fluctuations created by measurement noise that is injected in the system due to feedback. Direct MRAS offers a potential solution to reduce the tracking errors when there are large changes in the process parameters. Hence, direct MRAS control algorithm may fail to the robust systems. Indirect MRAS offers an effective solution to improve the control performance in the presence of parametric uncertainties and however, every time it is not possible to get the small tracking errors.In this paper modern heuristic optimization technique ESPSO method is proposed to find the trajectory of the TWIP-MR during its stabilization.

II. Inspiration

Most global optimization problems are nonlinear and thus difficult to solve, and they become even more challenging when uncertainties are present in objectivefunctions and constraints. Efficiency of a Optimization techniques depends upon the search algorithm. Most of the search techniques are single search stage. But in Eagle Strategy there are two searches one is called as Global search and the other is called as the Local Search.

Think like a Golden Eagle

"The Victorious strategist only seeks battle after the victory has been won, whereas he who is destined to defeat first fights and afterwards looks for victory."- Sun Tzu

The behaviour of Golden Eagles (*Aquila chrysaetos*)is inspiring. An eagle forages in its own territory by flying freely in a random manner much like then L´evy flights. Once the prey is sighted, the eagle will change its search strategy to an intensive chasing tactics so as to catch the prey as efficiently as possible. There are two important components to an eagle's hunting strategy: random search by L´evy flight (or walk) and intensive chase by locking its aim on the target.

III. Mathematical modelling

Dynamic Model

The Two Wheeled Mobile Robot is a Inverted Pendulum which mounted on a moving cart used as a Robot System which is shown in figure 3.1.Dynamic design of a TWMR can be modelled based on the following design assumptions:

1) The TWMR does not contain flexible parts;
2) There is at the most one steering link per wheel;
3) All steering axes are perpendicular to the surface of travel.

So, the equations that describe the kinematics and the dynamics of a nonholonomic constraint. In this research, a unicycle mobile robot is considered as a case study. The robot body is symmetrical around the perpendicular axis and the centre of mass is at the coordinate centre of the TWMR.

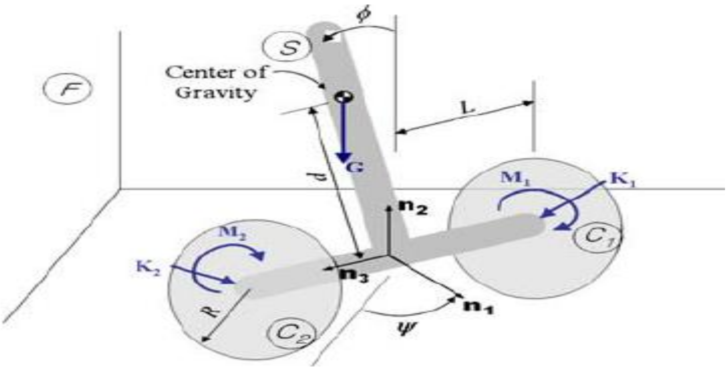

Fig.3.1TWIP – Mobile Robot

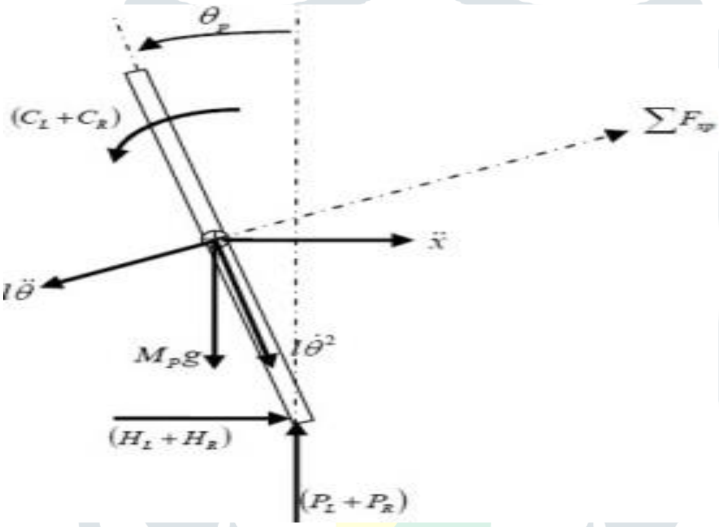

Fig. 3.2. Free Body Diagram of Chassis

Symbol	**Parameter**	**Value**
x	Horizontal displacement	[m]
$\frac{dx}{dt} = \dot{x}$	Linear Velocity	[m/s]
θ	Tilt Angle	[rad]
$\frac{d\theta}{dt} = \dot{\theta}$	Angular Velocity	[rad/s]
V_a	Applied Terminal Voltage	[Volt]
k_m	Motor's Torque Constant	[Nm/A]
k_e	Back EMF constant	[V-s/rad]
R	Terminal Resistance	[Ω]

l	Distance b/w Centre of wheel and Robot’s Centre of gravity	[m]
g	Gravitational constant	[m/s^2]
M_p	Mass of Robot’s chassis	[kg]
M_w	Mass of the wheel connected to both sides of the Robot	
I_p	Moment of inertia of Robot’s chassis	[kg-s^2]
I_w	Moment of inertia of the wheels	[kg-s^2]
r	Wheel Radius	[m]
C_R, C_L	Applied Torque from the motors to the wheels	
$H_R, H_L,$ P_R, P_L	Reaction Forces between the wheel and chassis	
C_R, C_L	Frictional forces b/w ground& wheels	

From DC Motor dynamics DC Motor Model is represented as state space representation as follows

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{k_m k_e}{I_R R} \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{k_m}{I_R R} & -\frac{1}{I_R} \end{bmatrix} \begin{bmatrix} V_a \\ \tau_a \end{bmatrix} \quad (3.1)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} \quad (3.2)$$

The equations which governs the behavior of TWIP-MR are formulated by using the free body diagram which is as shown in Figure 3.2

According to Newton’s law of motion, the sum of forces in horizontal direction can be expressed as

$$\sum f_x = M_p a \quad (3.3)$$

$$\left(H_R + H_L\right) = M_p \ddot{x} + M_p l \ddot{\theta}_p \cos\theta_p - M_p l \dot{\theta}_p^{\,2} \sin\theta_p \quad (3.4)$$

Similarly the sum of forces in perpendicular direction can be expressed as

$$\sum f_{xp} = M_p a \cos\theta_p \quad (3.5)$$

$$\left(H_R + H_L\right)\cos\theta_p + \left(P_R + P_L\right)\sin\theta_p - M_p g \sin\theta_p - M_p l \ddot{\theta}_p = M_p \ddot{x} \cos\theta_p \quad (3.6)$$

By simplifying the above two directional forces represented in equations (3.4) and (3.6) ,Non-Linear equations for TWIP-MR will be as follows

$$\left[I_p + M_p l^2\right]\ddot{\theta}_p - \frac{2K_m K_e}{Rr}\dot{x} + \frac{2K_m}{R} V_a + M_p g l \sin\theta_p = -M \ddot{x} \cos\theta_p \quad (3.7)$$

$$\left[2M_w + \frac{2I_w}{r^2} + M_p\right]\ddot{x} + \frac{2K_m K_e}{Rr^2}\dot{x} + M_p l \ddot{\theta}_p \cos\theta_p - M_p l \left(\dot{\theta}_p\right)^2 \sin\theta_p = \frac{2K_m}{Rr} V_a \quad (3.8)$$

To linearize the above system of equations which represents the TWIP-MR dynamic motions assume that the Robot is symmetrical (which means the desired balancing angle is set to zero) i.e $\theta_p = \pi + \phi$

Hence,above equations (3.7) and (3.8) are modified as follows

$$\left[I_p + M_p l^2\right]\ddot{\phi} - M_p \ddot{x} l - \frac{2K_m K_e}{Rr}\dot{x} - M_p g l \phi = -\frac{2K_m}{R} V_a$$

$$\frac{2K_m}{Rr} V_a = \left[2M_w + \frac{2I_w}{r^2} + M_p\right]\ddot{x} + \frac{2K_m K_e}{Rr^2}\dot{x} - M_p l \ddot{\phi}$$

State-Space representation for a Two Wheeled – IP Linear Displacement and Angular Displacements by neglecting the coupling coefficients are represented as follows

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \dfrac{-2K_m K_e}{Rr^2(2M_w + \frac{2I_w}{r^2} + M_p)} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{2K_m}{Rr(2M_w + \frac{2I_w}{r^2} + M_p)} \end{bmatrix} V_a \quad (3.9)$$

$$\begin{bmatrix} \dot{\phi} \\ \ddot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \dfrac{M_p g l}{(I_p + M_p l^2)} & 0 \end{bmatrix} \begin{bmatrix} \phi \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{2K_m}{R(I_p + M_p l^2)} \end{bmatrix} V_a \quad (3.10)$$

Based upon the above state space representation TWMR-IP is modelled as follows shown in the Figure 3.3

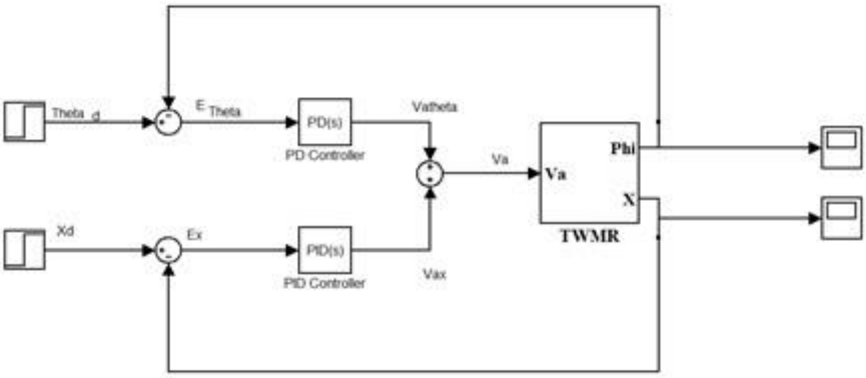

Figure 3.3 Block diagram of Two Wheeled Inverted Pendulum Mobile Robot with Conventional Controllers

The desired set point linear and angular positions are represented with the help of a standard second order system whose specifications are taken as damping ratio(zeta)= 0.7 and natural frequency of oscillations as ω_n=10 [rad /sec].
State space representation is as follows

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -2\xi\omega_n \end{bmatrix} \begin{bmatrix} x_{1m} \\ x_{2m} \end{bmatrix} + \begin{bmatrix} 0 \\ K\omega_n^2 \end{bmatrix} r(t)$$

IV. PROBLEM FORMULATION

This paper defines the Objective Function as reducing the error between the original TWIP-MR linear and angular displacements with respect to standard system to make TWIP-MR as a stabilized system. So, the objective function can be formulated as follows

$$f(e_x, e_\phi) = e_x^{\,T} P e_x + e_\phi^{\,T} Q e_\phi + a^T \alpha a + b^T \beta b \quad (4.1)$$

Where P and Q are positive definite symmetrical matrices. a and b are the vectors which contains the non-zero elements of A and B matrices of TWIP-MR modeling equations. α and β are the diagonal matrices with positive elements which determines the speed of adaption.

The above objective function is to be tuned by MRAS technique also. The corresponding Block diagram is as shown in the below Fig. 4.1. Later, ES-PSO is applied to optimize the above objective function.

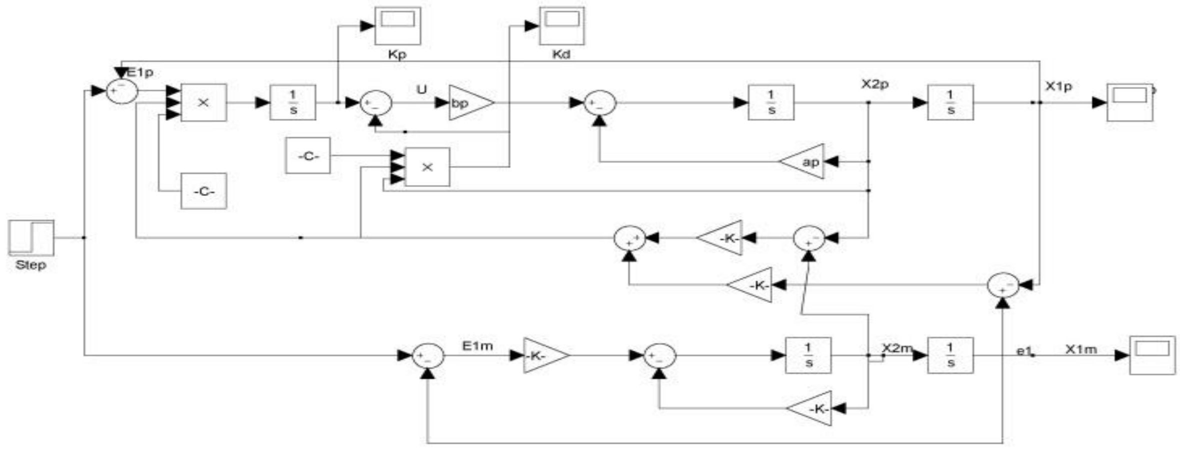

Fig. 4.1 Simulation Diagram for TWMR-IP without Filter circuit

V. ES-PSO ALGORITHM

Eagle Strategy with Particle Swarm Optimization Technique (ES-PSO) is a two stage process, developed by Yang. The foraging behaviour of eagles such as golden eagles or Aquila Chrysaetos is inspiring. An eagle forages in its own territory by flying freely in a random manner much like the L´evy flights. Once the prey is sighted, the eagle will change its search strategy to an intensive chasing tactics so as to catch the prey as efficiently as possible. There are two important components to an eagle's hunting strategy: random search by L´evy flight (or walk) and intensive chase by locking its aim on the target.

Now let us idealize the two-stage strategy of an eagle's foraging behaviour. Firstly, we assume that an eagle will perform the L´evy walk in the whole domain. Once it finds a prey it changes to a chase strategy. Secondly, the chase strategy can be considered as an intensive local search using any efficient metaheuristic algorithms such as the particle swarm optimization (PSO) to do concentrated local search.

Levy Distribution is given as follows:

$$L(s) \sim \frac{\lambda\Gamma(\lambda)\sin\left(\pi\lambda/2\right)}{\pi}\frac{1}{s^{1+\lambda}} \tag{5.1}$$

Where
$\Gamma(\lambda)$ is standard gamma function and s is a step length.
When $\lambda = 3$ it becomes Brownian motion
$\lambda = 2$ it becomes Cauchy distribution.

In a variable space, each particle has a position identified by $x_i^k = (x_{i1}^k, x_{i2}^k, \ldots.., x_{in}^k)$ and a velocity is identified by $v_i^k = (v_{i1}^k, v_{i2}^k, \ldots.., v_{in}^k)$. The position and velocity of each particle is updated by following expressions. If a particle has a best position, it is carried to the next. Additionally best positions are represented as pbest and the best position of all particles is represented by gbest.

$$v_i^{k+1} = w_i v_i^k + c_1 r_1 (pbest_i - x_i^k) + c_2 r_2 (gbest_i - x_i^k) \tag{5.2}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{5.3}$$

Where r_1 and r_2 are selected randomly in the range [0, 1] and c_1 and c_2 are acceleration coefficients that inspect the motion of particle. Weight Function is given by following expression.

$$w_i = w_{\max} - \frac{w_{\max} - w_{\min}}{k_{\max}} * k \tag{5.4}$$

Here $w_{\min} = 0.4$
$w_{\max} = 0.9$

VI. ES-PSO ALGORITHM

The Algorithm for the proposed Eagle Strategy with PSO method is as described below.

Step 1: Load the Objective Function and Two-Wheeled Mobile Robot parameters.
Step 2: Generate initial population randomly.
Step 3: Set Maximum number of iterations count.

Step 4: Find the Transfer Function of the Desired Adaptive Control system and obtain the state solutions of both plant and chosen Adaptive plant. Then, Find error expressions for both Linear and Angular Displacements.
Step 5: While k>number of Iterations

$$e_x(k+1) = e_x(k) + \alpha L(s,\lambda)$$

$$e_\phi(k+1) = e_\phi(k) + \alpha L(s,\lambda)$$

Global Search: Levy Flight

Where step length s=5,λ=1.5, α =1

$$L(s) \sim \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}$$

Then find the solutions for both Linear and Angular displacement errors using Global Search using above expressions.
Step 6: Choose global best (gbest) value from global search results for the local search reference.
Local Search: Update the displacement errors and Velocities by using the following formulas

$$v_i^{k+1} = w_i v_i^k + c_1 r_1(pbest_i - x_i^k) + c_2 r_2(gbest_i - x_i^k) \quad x_i^{k+1} = x_i^k + v_i^{k+1}$$

Where W is Inertia constant C1and C_2 are Correction Factors

Step 7: Update the Iteration count k=k+1Stop the Criteria based upon the maximum Iteration count or by choosing the Tolerance Value in error.

The overall Adaptive Control System for a Two Wheel Inverted Pendulum-Mobile Robot using ESPSO Block Diagram representation is as shown in Figure 6.1

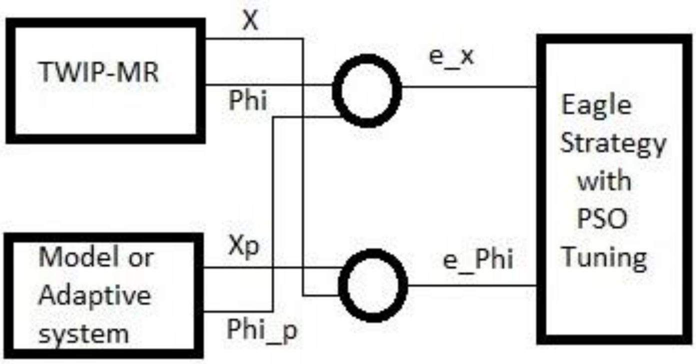

Figure 6.1: Overall Block Diagram of TWIP-MR with ESPSO Tuning

VII. SIMULATION RESULTS

The parameter values are considered of the considered Two wheeled Mobile Robot Inverted Pendulum are considered as follows : $I_p = 0.01$ [Kg-s^2], $I_w = 0.015$ [Kg-s^2], $M_p = 1.2$ [Kg], $M_w = 0.1$ [Kg], R = 5.25 Ω, r =0.05 [m], $K_m = 0.28$ [Nm/A], $K_e = 0.67$ [V-s/rad], g=9.81 [m/s^2], l = 0.1 [m]. The parameters of reference model are as follows: $\omega_n = 10$ rad/s , zeta =0.7

The parameters of ES-PSO are as follows : $C_1 = C_2 = 2$, $W_{min} = 0.4$, $W_{max} = 0.9$, λ = 2

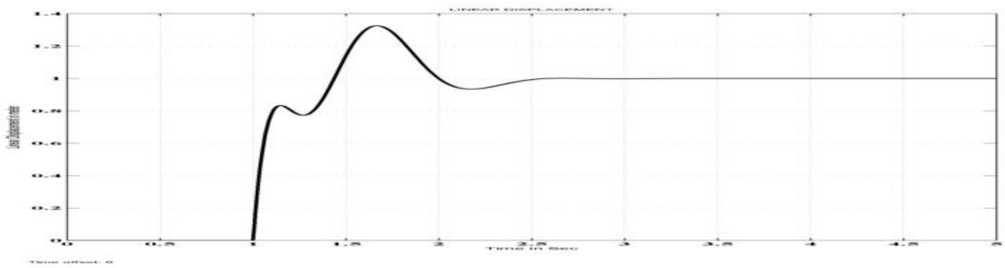

Fig 7.1: TWMR-IPs Linear Displacement with conventional PID Controllers

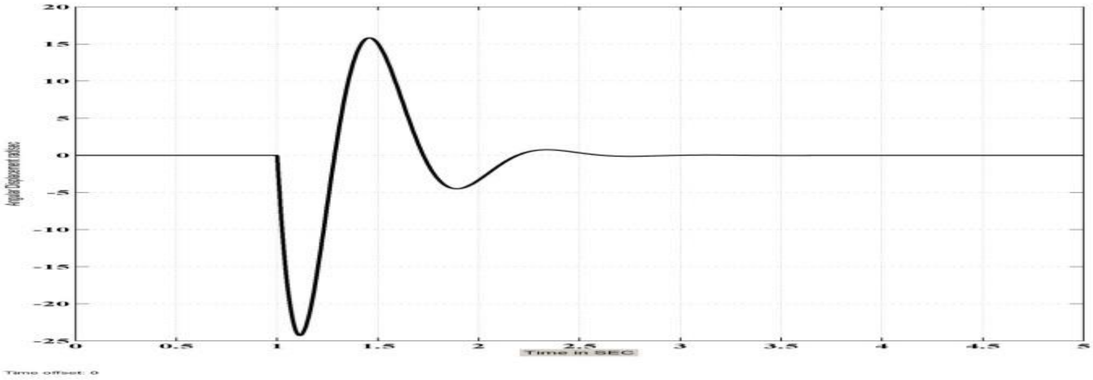

Figure 7.2: TWMR-IPs Angular Displacement with conventional PID Controllers

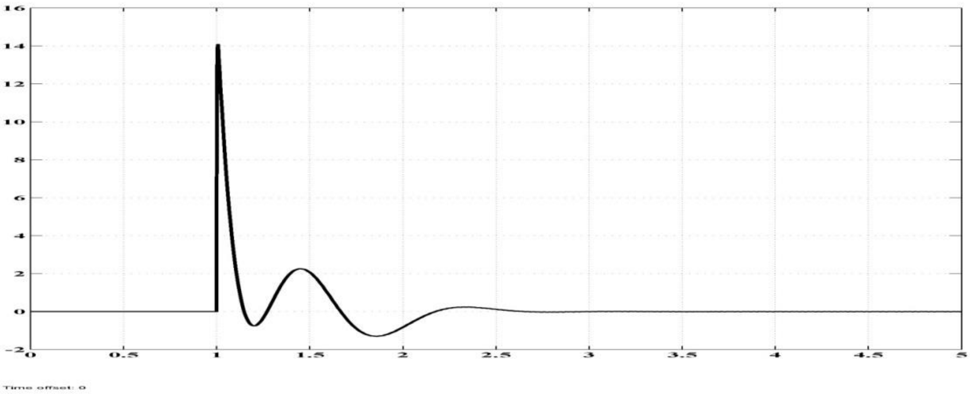

Figure 7.3: TWMR-IPs Linear Velocity with conventional PID Controllers

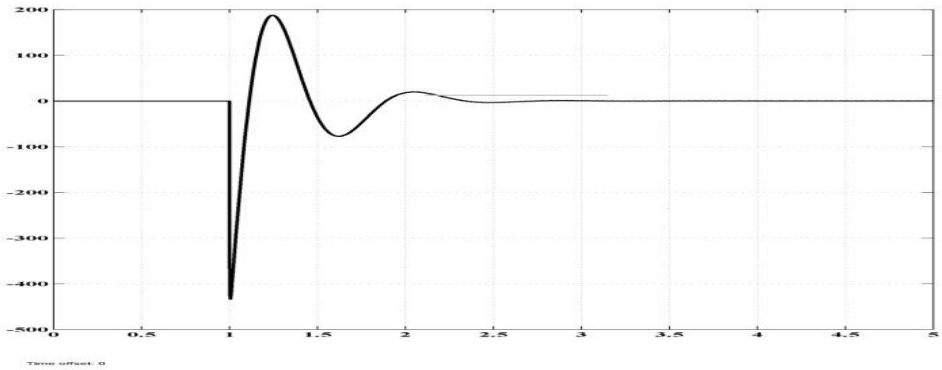

Figure 7.4: TWMR-IPs Angular Velocity with conventional PID Controllers

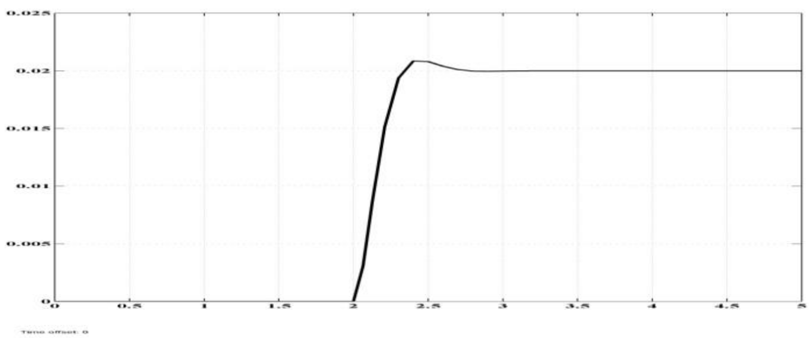

Figure 7.5: Desired Model Response

Time Domain Specifications of Reference Model:
Rise Time: 0.8000

Settling Time: 2.9800
Settling Min: 100.0000
Settling Max: 100.0000
Overshoot: 0
Undershoot: 1.7764e-015
Peak: 100.0000
Peak Time: 3

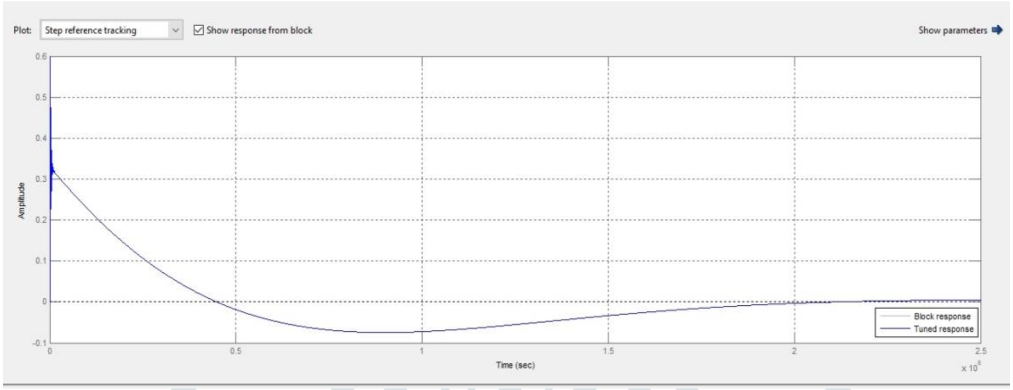

Figure 7.6 Tuned PD Controller gain

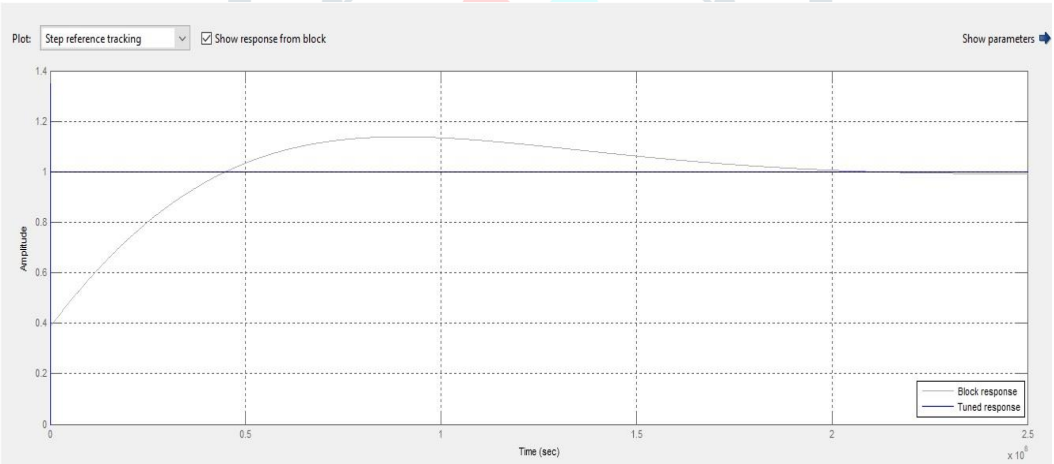

Figure 7.7 Tuned PID Controller gain

The Simulation Results Consists of 7 Columns. The first two Columns are Objective Function. 3rd and 4th columns are Linear and Angular Displacement errors. 5Th and 6Th Columns are the Updated values of Linear and Angular Displacement errors. 7Th Column corresponding to the Best Possible values of the objective function. The numbers of Iterations are here set to 30. Final Iteration values are attached in the following figure.

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0.0060	0.0060	0.0060	0.0060	-0.0093	-0.0012	1.0000
0.0070	0.0070	0.0070	0.0070	-0.0101	-0.0076	1.0000
0.0080	0.0080	0.0080	0.0080	-0.0051	-0.0027	1.0000
0.0090	0.0090	0.0090	0.0090	-0.0023	-0.0102	1.0000
0.0100	0.0100	0.0100	0.0100	-0.0125	-0.0080	1.0000
0.0110	0.0110	0.0110	0.0110	-0.0171	-0.0042	1.0000
0.0120	0.0120	0.0120	0.0120	-0.0092	-0.0018	1.0000
0.0130	0.0130	0.0130	0.0130	-0.0040	-0.0012	1.0000
0.0140	0.0140	0.0140	0.0140	-0.0192	-0.0243	1.0000
0.0150	0.0150	0.0150	0.0150	-0.0220	-0.0112	1.0000
0.0160	0.0160	0.0160	0.0160	-0.0282	-0.0100	1.0000
0.0170	0.0170	0.0170	0.0170	-0.0008	-0.0273	1.0000
0.0180	0.0180	0.0180	0.0180	-0.0018	-0.0112	1.0000
0.0190	0.0190	0.0190	0.0190	-0.0356	-0.0360	1.0000
0.0200	0.0200	0.0200	0.0200	-0.0177	-0.0038	1.0000
0.0210	0.0210	0.0210	0.0210	-0.0023	-0.0070	1.0000
0.0220	0.0220	0.0220	0.0220	-0.0284	-0.0044	1.0000
0.0230	0.0230	0.0230	0.0230	-0.0247	-0.0132	1.0000
0.0240	0.0240	0.0240	0.0240	-0.0412	-0.0025	1.0000
0.0250	0.0250	0.0250	0.0250	-0.0431	-0.0148	1.0000
0.0260	0.0260	0.0260	0.0260	-0.0498	-0.0031	1.0000
0.0270	0.0270	0.0270	0.0270	-0.0263	-0.0047	1.0000
0.0280	0.0280	0.0280	0.0280	-0.0489	-0.0446	1.0000
0.0290	0.0290	0.0290	0.0290	-0.0418	-0.0374	1.0000
0.0300	0.0300	0.0300	0.0300	0	0	1.0000
0.0310	0.0310	0.0310	0.0310	0	0	1.0000
0.0320	0.0320	0.0320	0.0320	0	0	1.0000
0.0330	0.0330	0.0330	0.0330	0	0	1.0000
0.0340	0.0340	0.0340	0.0340	0	0	1.0000
0.0350	0.0350	0.0350	0.0350	0	0	1.0000
0.0360	0.0360	0.0360	0.0360	0	0	1.0000
0.0370	0.0370	0.0370	0.0370	0	0	1.0000
0.0380	0.0380	0.0380	0.0380	0	0	1.0000
0.0390	0.0390	0.0390	0.0390	0	0	1.0000
0.0400	0.0400	0.0400	0.0400	0	0	1.0000
0.0410	0.0410	0.0410	0.0410	0	0	1.0000
0.0420	0.0420	0.0420	0.0420	0	0	1.0000
0.0430	0.0430	0.0430	0.0430	0	0	1.0000
0.0440	0.0440	0.0440	0.0440	0	0	1.0000
0.0450	0.0450	0.0450	0.0450	0	0	1.0000
0.0460	0.0460	0.0460	0.0460	0	0	1.0000
0.0470	0.0470	0.0470	0.0470	0	0	1.0000
0.0480	0.0480	0.0480	0.0480	0	0	1.0000
0.0490	0.0490	0.0490	0.0490	0	0	1.0000
0.0500	0.0500	0.0500	0.0500	0	0	1.0000

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